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Consistent regional fluxes of CH₄ and CO₂ inferred from GOSAT proxy XCH₄ : XCO₂ retrievals, 2010–2014

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Abstract. We use the GEOS-Chem global 3-D model of atmospheric chemistry and transport and an ensemble Kalman filter to simultaneously infer regional fluxes of methane (CH₄) and carbon dioxide (CO₂) directly from GOSAT retrievals of XCH₄ : XCO₂, using sparse ground-based CH₄ and CO₂ mole fraction data to anchor the ratio. This work builds on the previously reported theory that takes into account that (1) these ratios are less prone to systematic error than either the full-physics data products or the proxy CH₄ data products; and (2) the resulting CH₄ and CO₂ fluxes are self-consistent. We show that a posteriori fluxes inferred

from the GOSAT data generally outperform the fluxes inferred only from in situ data, as expected. GOSAT CH₄ and CO₂ fluxes are consistent with global growth rates for CO₂ and CH₄ reported by NOAA and have a range of independent data including new profile measurements (0–7 km) over the Amazon Basin that were collected specifically to help validate GOSAT over this geographical region. We find that large-scale multi-year annual a posteriori CO₂ fluxes inferred from GOSAT data are similar to those inferred from the in situ surface data but with smaller uncertainties, particularly over the tropics. GOSAT data are consistent with

smaller peak-to-peak seasonal amplitudes of CO₂ than either the *a priori* or in situ inversion, particularly over the tropics and the southern extratropics. Over the northern extratropics, GOSAT data show larger uptake than the *a priori* but less than the in situ inversion, resulting in small net emissions over the year. We also find evidence that the carbon balance of tropical South America was perturbed following the droughts of 2010 and 2012 with net annual fluxes not returning to an approximate annual balance until 2013. In contrast, GOSAT data significantly changed the *a priori* spatial distribution of CH₄ emission with a 40 % increase over tropical South America and tropical Asia and a smaller decrease over Eurasia and temperate South America. We find no evidence from GOSAT that tropical South American CH₄ fluxes were dramatically affected by the two large-scale Amazon droughts. However, we find that GOSAT data are consistent with double seasonal peaks in Amazonian fluxes that are reproduced over the 5 years we studied: a small peak from January to April and a larger peak from June to October, which are likely due to superimposed emissions from different geographical regions.

1 Introduction

Atmospheric growth of the two most abundant non-condensable greenhouse gases (GHGs), carbon dioxide (CO₂) and methane (CH₄), increases the absorption of Earth's outgoing infrared radiation (IR) with implications for the radiation budget of Earth's atmosphere and subsequent manifold changes in climate, including an increase in global mean temperatures. The most recent international climate agreement aims to limit the rise in global mean temperature to 2 °C, which will be attempted by reducing the emissions of human-driven (anthropogenic) GHGs. This approach necessarily assumes that we have good knowledge of emissions from all anthropogenic sectors so that targeted reductions are effective. It also implicitly assumes that the Earth's biosphere will continue to be a net annual sink for up to 40–60 % of anthropogenic CO₂ (e.g. Barlow et al., 2015) and the continued stability of natural reservoirs of CH₄. Current scientific knowledge, informed by mostly ground-based data and models, does not confidently support either assumption even on a continental scale. Here, we present the first multi-year record of self-consistent regional net fluxes (sources minus sinks) of CO₂ and CH₄ inferred from the Japanese Greenhouse gases Observing SATellite (GOSAT). We show these fluxes are significantly different from those inferred from ground-based data, particularly over tropical ecosystems, but are generally consistent with independent data throughout the troposphere.

Inferring CO₂ and CH₄ fluxes directly from atmospheric observations is an ill-posed inverse problem, with a wide range of scenarios that fit these data. Prior information is used to regularize the problem, with care taken to describe

data and prior uncertainties to avoid over- or under-fitting the data. There is a growing and progressive literature on estimating GHG fluxes in which an atmospheric chemistry transport model is used to relate observed atmospheric GHG mole fractions to atmospheric surface exchange fluxes. A number of approaches are used to minimize the model–observation residual to infer spatial and temporal variations in flux. Errors introduced by the incomplete and uneven coverage of current ground-based observation networks are compounded by atmospheric model errors (e.g. transport and chemistry) resulting in significant discrepancies between flux estimates inferred from different models on spatial scales < O(10 000 km) (e.g. Law et al., 2003; Yuen et al., 2005; Stephens et al., 2007; Peylin et al., 2013).

Space-borne observations of short-wave IR (SWIR) that are sufficiently precise to detect small changes in lower tropospheric CO₂ and CH₄ necessary for flux inference are beginning to improve the current understanding of these GHGs. GOSAT (Kuze et al., 2016), launched in 2009, was the first satellite designed purposefully to measure CO₂ and CH₄ columns using SWIR wavelengths. There is a growing body of literature that has inferred regional CO₂ and CH₄ fluxes from GOSAT dry-air CO₂ (XCO₂) and CH₄ (XCH₄) column mole fractions using the proxy and full-physics data products (Basu et al., 2013; Deng et al., 2014; Houweling et al., 2015; Bergamaschi et al., 2013; Takagi et al., 2014; Fraser et al., 2014). The resulting flux estimates (particularly for CO₂) are often found to be inconsistent with the results based on the surface network and with each other using different atmospheric transport models or using different versions of retrievals (Chevallier et al., 2014; Houweling et al., 2015). The reliability of the fluxes inferred from GOSAT XCO₂ retrievals (Reuter et al., 2014; Feng et al., 2016), considering bias in current retrievals (Feng et al., 2016) as well as the variations in temporal and spatial coverage (Liu et al., 2014), is still a subject of ongoing discussions.

We build on previous work that developed a novel approach to estimate simultaneously regional CO₂ and CH₄ flux estimates from the GOSAT XCH₄:XCO₂ ratio measurements, which had been until then used exclusively to develop “proxy” XCH₄ retrievals (Fraser et al., 2014). Previous work has shown that these ratios are less prone to the systematic bias that represents a substantial challenge to the full-physics data products. The underlying assumption of the proxy approach is that, by taking the ratio of the two retrieved values that have been fitted simultaneously in nearby spectral windows (1.65 and 1.61 µm), any interference due to cloud and aerosol scattering will be similar for both retrieved values and will be removed (Frankenberg et al., 2005, 2006). The ratio is then scaled by a model XCO₂ value, under the assumption that atmospheric gradients of XCO₂ are much smaller than XCH₄, to generate XCH₄ proxy retrievals. Data products generated by the proxy approach are more robust against scattering than the full-physics approach so that there are more usable retrievals over geographical re-

gions that are compromised by seasonal aerosol and cloud distributions, e.g. tropical South America. Fraser et al. (2014) used a series of numerical experiments and the maximum a posteriori (MAP) approach to show that these XCH₄ : XCO₂ ratios could be used, in conjunction with in situ observations of CH₄ and CO₂ mole fractions, to simultaneously estimate regional CO₂ and CH₄ fluxes. Pandey et al. (2016) used a similar approach but using a 4-D variational assimilation approach to infer XCO₂ and XCH₄ fluxes for 20 months from April 2009. They found that after correcting biases in the XCH₄ : XCO₂ retrievals, the ratio inversion results in similar agreement with independent CO₂ and CH₄ observations, as other inversions based on the in situ data only or based on individual GOSAT XCH₄ and XCO₂ products. Here, we use an ensemble Kalman filter (EnKF) to assimilate the XCH₄ : XCO₂ ratio data (UoLv6; Parker et al., 2015) from January 2009 to December 2014, inclusive. A comparison between the UoLv6 data set and the ground-based XCH₄ and XCO₂ data from the Total Carbon Column Observing Network (TCCON) shows a bias of about 0.3 %. We use individual in situ and GOSAT observations (instead of monthly means; Fraser et al., 2014) to estimate monthly fluxes at a higher spatial resolution than Fraser et al. (2014).

In the next section, we describe the ensemble Kalman filter approach, the observations we use to infer the CO₂ and CH₄ fluxes and those we use to evaluate the resulting posterior flux estimates, and a description of the numerical experiments. In Sect. 3, we describe our results, with a particular focus on tropical South America where we compare our a posteriori model with new aircraft measurements. We conclude the paper in Sect. 4.

2 Methods and data

2.1 Ensemble Kalman filter

We develop an existing EnKF framework that has been used to estimate CO₂ (Feng et al., 2009, 2011, 2016) and CH₄ fluxes from the in situ or space-based measurements of their atmospheric observations (Fraser et al., 2013). In this study, the state vectors are regional fluxes of CO₂ and CH₄ at location x and time t as

$$f_p^g(x, t) = f_0^g(x, t) + \sum_i c_i^g \text{BF}_i^g(x, t), \quad (1)$$

where g denotes CO₂ or CH₄ tracer gas and $f_0^g(x, t)$ describes the a priori estimates of CO₂ or CH₄ fluxes. Following Fraser et al. (2014), our basis function set $\text{BF}_i^g(x, t)$ is defined as the pulse-like (monthly) CO₂ or CH₄ fluxes from different sectors over predefined geographic regions. The coefficients c_i^g for both the CO₂ and CH₄ fluxes form a joint state vector \mathbf{c} to be estimated by optimally fitting the model to the data.

In the ensemble Kalman filter framework, the prior flux error covariance \mathbf{P} is represented by an ensemble of pertur-

bations of the coefficients $\Delta\mathbf{C}$: $\mathbf{P} = \Delta\mathbf{C}\Delta\mathbf{C}^T$, where T represents the matrix transpose. The a posteriori coefficient estimates are given by

$$\mathbf{c}_a = \mathbf{c}_f + \mathbf{K}(\mathbf{y}_{\text{obs}} - H(\mathbf{c}_f)), \quad (2)$$

where \mathbf{c}_a , \mathbf{c}_f are the prior and posterior estimates, respectively; \mathbf{y}_{obs} are the observations; and H is the observation operator that relates surface fluxes (i.e. the coefficients) to the observation data (described below) and includes the atmospheric transport model (Fraser et al., 2014).

The Kalman gain matrix \mathbf{K} in Eq. (2) is approximated by Feng et al. (2009):

$$\mathbf{K} \approx \Delta\mathbf{C}\Delta\mathbf{Y}^T[\Delta\mathbf{Y}\Delta\mathbf{Y}^T + \mathbf{R}]^{-1}, \quad (3)$$

where \mathbf{R} is the observation error covariance, and $\Delta\mathbf{Y}^T = H(\Delta\mathbf{C})$ projects the flux perturbation (coefficients) ensemble $\Delta\mathbf{C}$ to observation space. We use the GEOS-Chem global 3-D chemistry transport model (v9.02) to relate the fluxes to the observation space. For the experiments reported here, we run the chemistry transport model (CTM) at a horizontal resolution of 4° (latitude) × 5° (longitude), driven by the GEOS-5 (GEOS-FP for 2013 and 2014) meteorological analyses from the Global Modeling and Assimilation Office Global Circulation Model based at NASA Goddard Space Flight Center. We use monthly 3-D fields of the hydroxyl radical from the GEOS-Chem HO_x-NO_x-O_x chemistry simulation to describe the main oxidation sink of CH₄ (Fraser et al., 2014). We use a 4-month moving lag window to reduce the computational costs related to the projection of the perturbation ensemble into the observation space for longer time periods (Feng et al., 2013, 2016).

Where possible, we use consistent emission inventories for CO₂ and CH₄: monthly biomass burning emission (GFEDv4.0; van der Werf et al., 2010) and monthly fossil fuel emissions (ODIAC; Oda and Maksyutov, 2011). To describe atmospheric CO₂ variations, we also use monthly-resolved climatological ocean fluxes (Takahashi et al., 2009) and 3-hourly terrestrial biosphere fluxes (CASA; Olsen and Randerson, 2004). To describe atmospheric CH₄ variations, following Fraser et al. (2014), we use prescribed annual inventories for emissions from oil and gas production, coal mining, ruminant animals (Olivier et al., 2005), termites, and hydrates (Fung et al., 1991). We use monthly-resolved emissions for rice paddies and wetlands for 2009, 2010, and 2011 (Bloom et al., 2012). From January 2012, we fix the rice paddy and wetland emissions to their monthly means between 2009 and 2011. We also include a simple soil sink of CH₄ (Fraser et al., 2014).

We define the pulse-like basis functions (Eq. 1) guided by the TransCom-3 regions (Gurney et al., 2002), with each continental region further divided equally into four subregions. Figure 1 shows the 44 land regions and 11 ocean regions that we use in this study; in comparison, Fraser et al. (2014) used 11 land regions and 1 ocean region. We describe the inversion

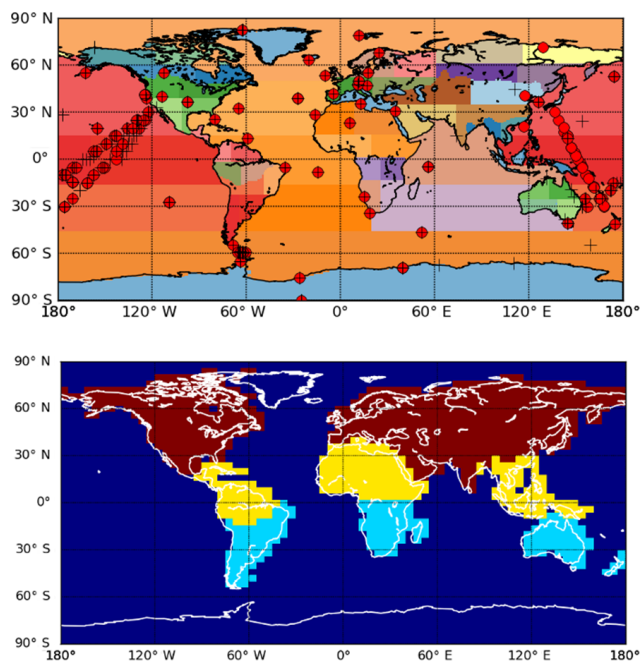


Figure 1. Top panel indicates the geographic basis functions used in our CO₂ and CH₄ flux inversion experiments. There are 44 land and 11 ocean regions. The red dots and the black crosses represent the locations of the NOAA in situ CO₂ and CH₄ observations that we assimilate in both the ratio inversion and the in situ only inversion. Geographical regions are based on those used by the TransCom experiments (Gurney et al., 2002), but we split each TransCom land region into four subregions denoted by different colours. Bottom panel indicates the definition of the aggregated northern (red), tropical (yellow), and southern (light blue) land regions.

on these smaller geographic regions to help reduce aggregation errors associated with fluxes being estimated on a coarse spatial resolution (Patra et al., 2005).

We distinguish CO₂ fluxes between four categories: (1) ocean fluxes; (2) anthropogenic emissions; (3) biomass burning; and (4) terrestrial biospheric fluxes. For CH₄ fluxes, we distinguish between six categories: (1) ocean fluxes; (2) anthropogenic emissions from coal mining; (3) anthropogenic emissions from oil and gas production, fossil fuel combustion, and others; (4) biomass burning; (5) natural fluxes from wetlands and rice paddies; and (6) natural fluxes from termites, hydrates, and others. In total, we have 143 monthly basis functions for CO₂ and 231 monthly basis functions for CH₄.

We assume an a priori uncertainty of 60 % for the coefficients corresponding to the natural CO₂ and CH₄ fluxes, and for CH₄ emissions from coal mines. We assume an a priori uncertainty of 40 % for CO₂ anthropogenic emissions, CO₂ and CH₄ ocean fluxes, and anthropogenic emission of CH₄ from the oil and gas industry. We also assume that a priori errors for the same categories are correlated with a spatial correlation length of 800 km and with a temporal correlation

of 1 month (Feng et al., 2016). We assume that fire emissions of CO₂ and CH₄ are correlated with a correlation coefficient of 0.5, accounting for the variation and uncertainty of the fire emission factors (Parker et al., 2016).

2.2 Observations

We assimilated GOSAT XCH₄ : XCO₂ retrievals and in situ surface observations of CO₂ and CH₄ mole fraction. We use version 6 of the proxy GOSAT XCH₄ : XCO₂ retrievals from the University of Leicester, UK, including both the nadir observations over land and glint observations over ocean. Previous analyses have shown that these retrievals have a bias of 0.3 %, with a single sounding precision of about 0.72 % (Parker et al., 2015, 2011). In our experiments, we globally remove this 0.3 % bias from the GOSAT proxy data. We assume that each single GOSAT proxy XCH₄ : XCO₂ ratio retrieval has an uncertainty of 1.2 % to account for possible model errors, including the errors in atmospheric chemistry and transport.

We also assimilate CO₂ and CH₄ mole fraction observations at surface-based sites, which help anchor the GOSAT ratio observations (Fraser et al., 2014). Figure 1 shows the sites we use from the NOAA observation network (Dlugokencky et al., 2015). We assume uncertainties of 0.5 ppm and 8 ppb for the in situ observations of CO₂ and CH₄, respectively. We also assume a model error of 1.5 ppm and 15 ppb for CO₂ and CH₄, respectively. We adopt a larger percentage for the CH₄ model error to account for difficulties in modelling chemical sinks of CH₄ in atmosphere (Patra et al., 2011; Fraser et al., 2013). A robust description of model error remains a major challenge for this and similar studies. We have assumed a simple formulation to describe model error, which will not fully account for impacts of errors from, for example, model atmospheric transport on resulting CO₂ and CH₄ flux estimates.

To determine the importance of the ratio data, we run twin sets of experiments: (1) “ratio” experiments that include the GOSAT data and the in situ data sets, and (2) “in situ” experiments that use only the in situ surface data.

2.3 Independent data to evaluate a posteriori estimates

We use independent observations of atmospheric CO₂ and CH₄ mole fraction to evaluate the atmosphere mole fractions that correspond to the a posteriori fluxes from our inversions. These observations include data collected by TCCON and by four aircraft campaigns. To improve the readability of the main text, we have placed much of the text and many of the figures associated with the evaluation of the a posteriori fluxes in Appendix A.

TCCON is a global network of ground-based Fourier transform spectrometer (FTS) instruments that measure, among other compounds, the total atmospheric columns of CO₂ and CH₄ (Wunch et al., 2011). We use the bias-

corrected TCCON XCO₂ and XCH₄ data at all available sites from the recent GGG2014 release of the TCCON data set (Wunch et al., 2015). For a comprehensive description of the network and the available data from each TCCON site, we refer the reader to the TCCON project page (e.g. Blumenstock et al., 2014; De Maziere et al., 2014; Deutscher et al., 2015; Dubey et al., 2014; Feist et al., 2014; Griffith et al., 2014a, b; Hase et al., 2015; Iraci et al., 2014, 2016; Kivi et al., 2014; Morino et al., 2014a, b; Notholt et al., 2014; Sherlock et al., 2014a, b; Strong et al., 2014; Sussmann and Rettinger, 2014; Te et al., 2014; Warneke et al., 2014; Wennberg et al., 2014a, b, c, 2015).

We also use aircraft measurements from four projects to evaluate our a posteriori model concentrations: (1) data collected during experiments 1–5 from the HIPPO pole-to-pole observations (HIPPO) that provide latitude–altitude cross sections of tropospheric mole fractions of CO₂ and CH₄ (and other tracers) covering dates from 2009 to 2011 (Wofsy et al., 2011); (2) data collected by commercial airliners as part of the Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container (CARIBIC) experiment, which are mainly at cruise altitudes, but also in ascent/descent over airports (Brenninkmeijer et al., 2007; Schuck et al., 2009); (3) bi-weekly aircraft measurements (surface to 4 km) collected from 2010 to 2012 at four sites over Brazil by IPEN (Instituto de Pesquisas Energéticas e Nucleares) over the Amazon rainforest (AMAZONICA; Gatti et al., 2014); Rio Branco (RBA), Tabatinga (TAB), Alta Floresta (ALF), and Santarém (SAN); and (4) aircraft measurements conducted by IPEN for the FAPESP/NERC-funded Amazonian Carbon Observatory (ACO; Webb et al., 2016) close to two of the AMAZONICA sites from 2012 to 2014: Salinópolis (SAH) and Rio Branco (RBH). These two sites were chosen to best represent air before and after travelling across the Amazon Basin. The purpose of these flights was to improve validation of GOSAT XCH₄ and XCO₂ data over the Amazon Basin so we flew from the surface to 7 km to capture more of the atmospheric column that GOSAT observes. A detailed description of ACO can be found in Webb et al. (2016), and comparison of these data against GOSAT XCH₄ : XCO₂ data are shown below.

3 Results

3.1 CO₂ fluxes

Figure 2 shows that the in situ only and the ratio inversions result in similar annual net CO₂ flux estimates (averaged for 2010 to 2014) over temperate land regions. But compared to the in situ only inversion, the ratio inversion shows a larger net emission over tropical South America, and a smaller net emission from tropical Asia, although the differences are usually within the 1 σ uncertainties. We also find that the a

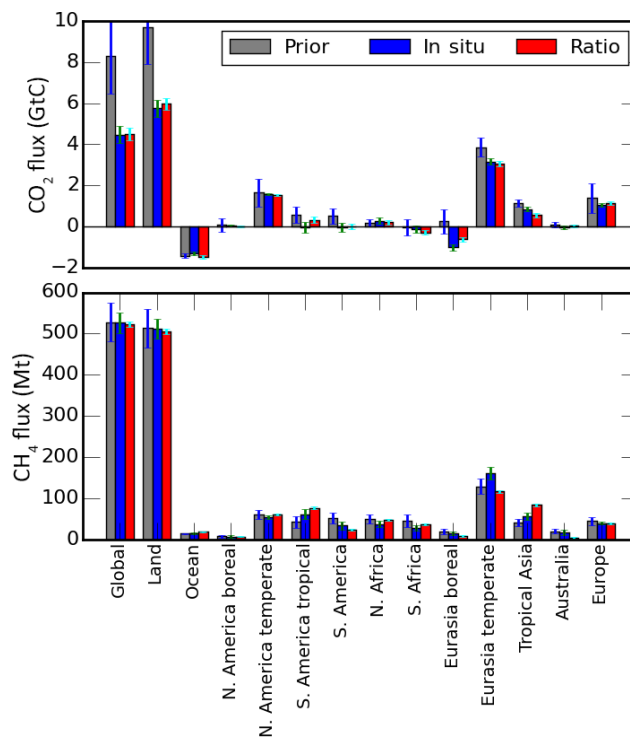


Figure 2. Annual mean (2010–2014, inclusive) regional net fluxes of (top) CO₂ and (bottom) CH₄ inferred from the (red) ratio experiments and the (blue) in situ experiments. The grey columns represent the a priori estimates and the vertical lines superimposed on the columns denote 1 σ error. Geographical regions are as defined in Fig. 1.

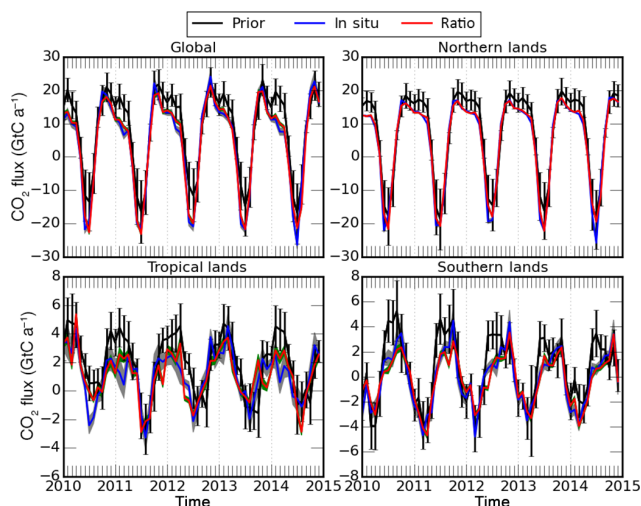
posteriori fluxes for the ratio inversion generally have smaller uncertainties, in particular, over tropical land regions.

Figure 3 and Table 1 compare the time series of the prior and posterior global net CO₂ flux estimates. They show that global annual a posteriori net flux estimates are 40–60 % smaller than the a priori estimates (Table 1) due to a smaller net emission during boreal winter and a larger net uptake during the boreal summer (Fig. 3). The corresponding global annual CO₂ growth rate agrees with NOAA estimates, inferred from in situ observations, typically within 0.15 ppm a⁻¹, except for 2013 when the inversions are 0.3 ppm a⁻¹ lower than the NOAA-reported value.

Figure 3 also shows that the monthly a posteriori flux estimates by the in situ and ratio inversions are similar over the northern landmasses (Fig. 1), with the exception of the summer in 2014 when the ratio inversion shows significantly smaller uptake. Over the tropical landmasses, a posteriori fluxes from the ratio inversion show a much smaller seasonal cycle, with exception of boreal summer months in 2014 when these fluxes have larger uptake. In general, uncertainties for the monthly fluxes inferred by the ratio inversion (GOSAT plus in situ data) are smaller (up to 30 %) than using only the in situ data. This reflects the poor spatial coverage of

Table 1. A priori and a posteriori estimates of the annual net CO₂ fluxes for 2010 to 2014 for the global and three contributing regions: (1) northern landmasses, (2) tropical landmasses, and (3) southern landmasses. Uncertainties of 1 σ are given in the brackets.

Region	Estimate	2010 GtC a ⁻¹	2011 GtC a ⁻¹	2012 GtC a ⁻¹	2013 GtC a ⁻¹	2014 GtC a ⁻¹
Global	Prior	8.64 (1.64)	7.52 (1.76)	8.72 (1.57)	7.97 (1.63)	8.10 (1.64)
	In situ	4.83 (0.37)	3.54 (0.35)	5.10 (0.34)	4.61 (0.34)	4.14 (0.36)
	Ratio	4.87 (0.25)	3.43 (0.25)	5.08 (0.24)	4.66 (0.24)	4.15 (0.26)
Northern lands	Prior	6.63 (1.47)	6.81 (1.60)	7.52 (1.44)	7.51 (1.48)	7.2 (1.53)
	In situ	4.60 (0.15)	4.47 (0.14)	5.07 (0.15)	4.89 (0.14)	4.90 (0.15)
	Ratio	4.68 (0.11)	4.81 (0.11)	5.38 (0.11)	5.05 (0.11)	5.30 (0.11)
Tropical lands	Prior	2.57 (0.44)	1.55 (0.46)	1.95 (0.38)	1.53 (0.44)	1.76 (0.43)
	In situ	1.31 (0.28)	0.70 (0.29)	1.08 (0.26)	1.22 (0.27)	1.04 (0.27)
	Ratio	1.63 (0.18)	0.59 (0.18)	1.00 (0.17)	1.21 (0.18)	1.03 (0.19)
Southern lands	Prior	0.84 (0.57)	0.56 (0.57)	0.64 (0.49)	0.32 (0.56)	0.53 (0.45)
	In situ	0.03 (0.25)	−0.50 (0.25)	0.15 (0.22)	−0.27 (0.23)	−0.38 (0.24)
	Ratio	0.09 (0.15)	−0.56 (0.16)	0.06 (0.15)	−0.31 (0.16)	−0.52 (0.16)

**Figure 3.** The net monthly CO₂ fluxes inferred by the in situ only inversion (blue) and the ratio inversion (red), compared to the prior estimates (black). The vertical lines (envelopes) represent the prior (posterior) uncertainties. In the plots, we aggregate CO₂ fluxes of all four categories to the net monthly values over four predefined global regions (Fig. 1): (a) global, (b) northern lands, (c) tropical lands, and (d) southern lands.

the current in situ observing network particularly over tropical ecosystems (Fig. 1). Over the southern landmasses, the a posteriori fluxes for the two inversions are similar and typically within their uncertainties. We find that both inversions show a gradual reduction in the peak-to-trough amplitude, which appears to support a similar downward trend in the a priori estimates from about 9.0 GtC a⁻¹ between 2010 and 2011 to about 7.5 GtC a⁻¹ between 2013 and 2014. A posteriori fluxes also consistently show lower net emissions than a priori values during austral winter months.

3.2 CH₄ fluxes

Figure 2 shows that a priori and the a posteriori global annual net CH₄ flux estimates are similar (520 Mt a⁻¹ for the a priori versus 518 Mt a⁻¹ for the ratio inversion), but their geographical distributions are significantly different. The ratio and in situ only inversions show much larger emissions than the a priori estimates over tropical lands, by up to 50 % larger for tropical South America and for tropical Asia (Fig. 2). This increase is partially offset by reduced emissions at midlatitudes (e.g. temperate South America). Over Eurasian temperate areas, we find that the ratio inversion has 15 % smaller emissions than the a priori estimates, but the fluxes inferred from the in situ surface data for the same region are 25 % higher than the a priori (Fig. 2), which is due to the in situ network having little sensitivity to emissions over a large part of Eurasian temperate areas, in particular over south-east China where there are large CH₄ sources from wetlands and rice paddies. Figure 2 also shows that the ratio inversion has much smaller (up to 60 %) uncertainties than the in situ inversions over almost all TransCom land regions, which is due to better spatial observation coverage of GOSAT proxy data.

Figure 4 shows that, at the global scale, the monthly a posteriori fluxes inferred from the ratio and in situ inversions have larger seasonal variations than the a priori: a typical seasonal minimum of about 450 Mt a⁻¹ and a typical maximum of 680 Mt a⁻¹, compared to the a priori that have a minimum of 480 Mt a⁻¹ and a maximum of 620 Mt a⁻¹. The larger a posteriori seasonal variation is largely due to the seasonal cycle over northern landmasses that is driven by varying wetland and fire CH₄ emissions. The ratio inversions also show a muted peak emission of typically 30 Mt a⁻¹ during January to February, partially due to peak emissions over southern landmasses during the austral summers. Over

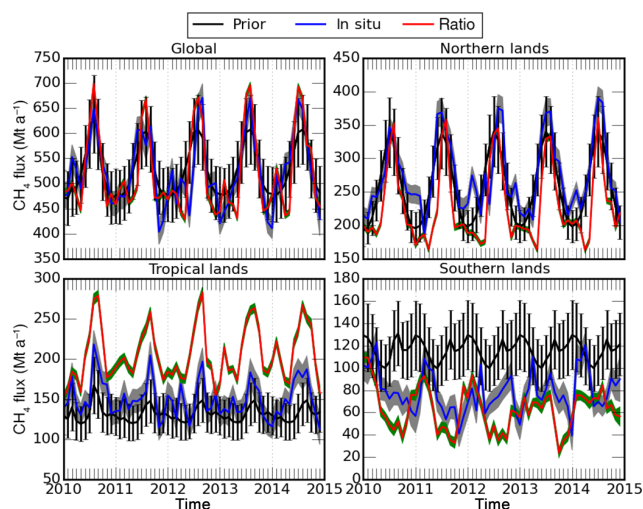


Figure 4. The same as Fig. 3 but for CH₄ fluxes.

Northern Hemisphere landmasses, the in situ inversion is systematically 5–10 % higher than the ratio inversion from 2010 to 2014. Over the tropics, we find that a posteriori tropical fluxes from the ratio and in situ inversions are generally larger than a priori estimates. Also, the ratio a posteriori fluxes are systematically higher than those inferred from the in situ surface data, and show a small upward annual trend (Table 2). Over this region, we also find that the ratio inversion consistently shows a double-peak structure with a small peak between January and April and a larger peak between June and October (Fig. 4). This is not shown by the in situ inversion or by the a priori inventory. A posteriori fluxes for the southern landmasses are generally lower by 30–50 Mt a^{−1} than the a priori values, which, together with northern landmasses, partially offset the increase in tropical CH₄ emissions (Fig. 4). Over Southern Hemisphere landmasses, the seasonal cycles of the ratio and in situ inversions are similar, although the ratio inversion generally has lower seasonal minima, with the exception of 2014 when the phase of the ratio inversion was the opposite of the in situ inversion.

3.3 Model evaluation

In general, the ratio inversion shows the best agreement with independent CH₄ observations, particularly over lower latitudes. A posteriori improvements to the CO₂ simulation are relatively small. We find that both the model CO₂ and CH₄ concentrations reproduce the large-scale spatial (e.g. the north–south gradient) and temporal (seasonal cycle) variations in the HIPPO and CARIBIC data (Sect. 2.3). The a posteriori simulations reproduce the observed TCCON XCH₄ and XCO₂ variations. Over most TCCON sites, the a posteriori XCO₂ model biases are within 0.8 ppm (< 0.2 %), and the standard deviations are smaller than 1.6 ppm. The typical model biases for model XCH₄ data are smaller than 10 ppb (i.e. < 0.6 %), with a standard deviation smaller than 15 ppb.

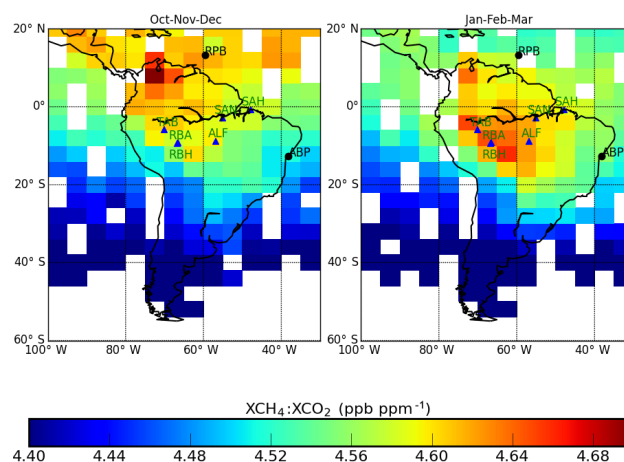


Figure 5. GOSAT XCH₄ : XCO₂ ratios over tropical South America (Fig. 1) described on the GEOS-Chem 4° (latitude) by 5° (longitude) averaged over (left) October to December 2013, inclusive, and (right) January to March 2014, inclusive. Black dots represent two NOAA in situ sites RPB (Ragged Point, Barbados) and ABP (Arembepe, Bahia, Brazil), and triangles represent independent AMAZONICA sites (RBA, ALF, TAB, SAN) and two ACO sites (RBH, SAH), which are described in the main text.

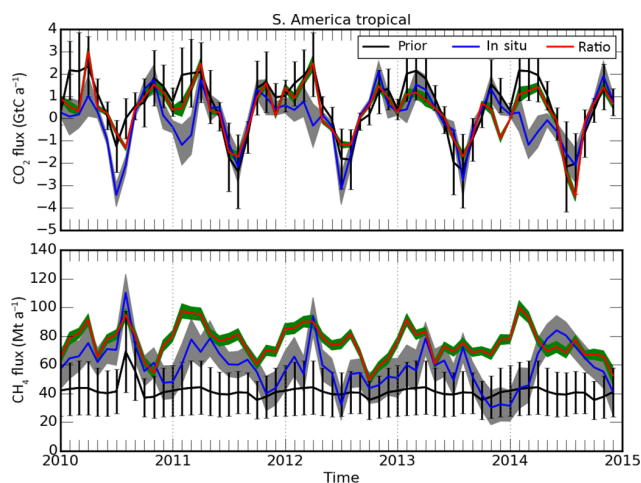
For more details, we refer the reader to Appendix A, where we show pictorially the comparisons between observations and the ratio, and in situ a posteriori CO₂ and CH₄ mole fractions.

Here, we focus on tropical South America (Fig. 1) for three reasons. First, in situ surface data are particularly sparse over this geographical region, including two sites (Fig. 5) over which we use the observed CO₂ and CH₄ mole fractions to constrain flux estimates: Arembepe, Bahia, Brazil (ABP; −12.770° latitude, −38.170° longitude) and Ragged Point, Barbados (RPB; 13.165° latitude, −59.432° longitude). Second, they include vulnerable ecosystems that have recently experienced several widespread drought conditions in 2010 and 2012 (see, for example, Lewis et al., 2011; Rodrigues and McPhaden, 2014), which have affected their ability of absorbing carbon (Doughty et al., 2015) and increased fire emissions (Gatti et al., 2014; Alden et al., 2016). And third, we report new aircraft profile measurements from the ACO (Webb et al., 2016) that was designed specifically to evaluate GOSAT column observations of CH₄ and CO₂ (Sect. 3).

Figure 6 shows that the a posteriori monthly CH₄ and CO₂ flux estimates over tropical South America from the ratio inversion are significantly different from the in situ inversion, as expected given the in situ surface data coverage. However, monthly a posteriori CO₂ fluxes from the ratio inversion are not always statistically different from the a priori, reflecting the large a priori uncertainties associated with fluxes over this region. The in situ inversion typically has larger uptake during the dry season (May to September) and smaller emissions during the wet seasons than the ratio inversion. Because the

Table 2. The same as Table 1 but for CH₄ fluxes.

Region	Estimate	2010 Mt a ⁻¹	2011 Mt a ⁻¹	2012 Mt a ⁻¹	2013 Mt a ⁻¹	2014 Mt a ⁻¹
Global	Prior	519.3 (59.9)	517.1 (58.5)	521.1 (58.7)	521.1 (58.7)	521.1 (58.7)
	In situ	524.8 (23.9)	509.8 (25.2)	513.9 (24.8)	509.3 (24.3)	529.2 (24.2)
	Ratio	521.2 (6.2)	508.1 (6.5)	508.4 (6.3)	514.8 (5.9)	527.8 (7.1)
Northern lands	Prior	250.3 (36.4)	253.4 (36.6)	256.2 (36.9)	256.2 (36.9)	256.2 (36.9)
	In situ	262.6 (14.4)	272.3 (16.5)	270.9 (16.4)	269.8 (15.8)	277.0 (14.5)
	Ratio	230.4 (4.4)	219.2 (4.5)	227.7 (4.5)	226.8 (4.3)	227.8 (4.7)
Tropical	Prior	132.3 (25.9)	128.4 (24.1)	129.2 (24.2)	129.2 (24.2)	129.2 (24.2)
	In situ	156.4 (15.7)	146.2 (15.3)	147.2 (15.6)	142.4 (15.7)	147.8 (15.2)
	Ratio	198.0 (5.8)	203.3 (5.8)	200.1 (5.7)	207.1 (5.2)	207.3 (5.9)
Southern lands	Prior	115.4 (26.7)	114.1 (26.2)	114.3 (26.1)	114.3 (26.1)	114.3 (26.1)
	In situ	84.3 (11.6)	70.1 (11.8)	74.5 (10.8)	75.8 (10.8)	83.0 (11.8)
	Ratio	68.1 (4.5)	61.0 (4.6)	56.5 (4.3)	56.3 (4.2)	67.5 (4.9)

**Figure 6.** The same as Fig. 3 but for CO₂ and CH₄ fluxes over tropical South America (Fig. 1).

in situ flux estimates over this geographical region rely on observation far away, they are particularly sensitive to a priori uncertainties, as expected. We find that assuming a global a priori uncertainty that is 50 % smaller than our control run results in an additional net emission of 0.4 GtC a⁻¹ over tropical South America in 2010. Including the GOSAT ratio data into that sensitivity inversion leads to a smaller net decrease (of 0.13 GtC a⁻¹) in emissions.

Table 3 shows that the a posteriori annual fluxes inferred by the ratio inversion are significantly larger than the in situ inversion in 2010, 2011, and 2012 by about 0.7, 0.4, and 0.5 GtC, respectively. A posteriori fluxes from the ratio inversion show net emissions are smaller in 2013 and 2014 than in 2010 or 2012, which is due to larger uptake in the dry season and smaller emissions in the wet seasons (Fig. 6). This result reveals the continental-scale impact of the severe droughts in

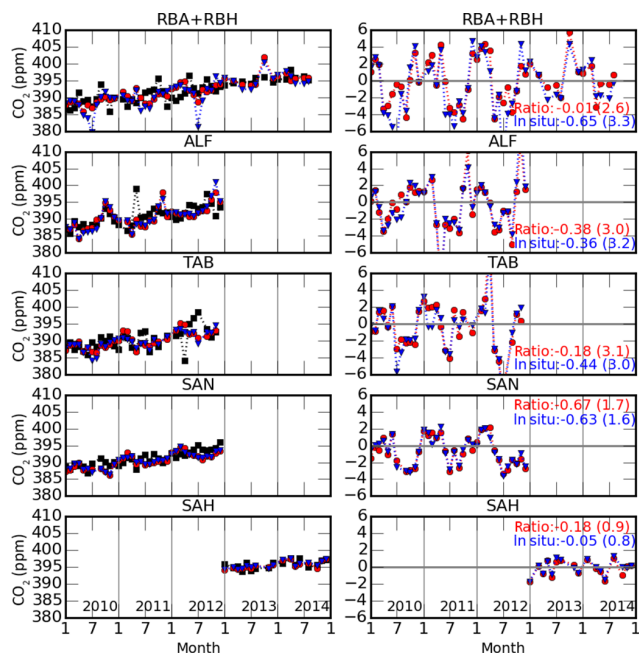
2010 and 2012 over tropical Southern America. Our result for 2010 is consistent with recent studies based on regional-scale AMAZONICA aircraft observations (Gatti et al., 2014; van der Laan-Luijkx et al., 2015; Alden et al., 2016). The in situ inversion fails to reproduce this increase in net emissions during the 2010 dry season, instead showing a large uptake (Fig. 6).

A posteriori CH₄ fluxes from the ratio inversion are systematically higher than the in situ inversion (Fig. 6). This discrepancy is particularly large from October 2013 to March 2014 when the in situ inversion is lower than typical seasonal values observed during previous years. Figure 5 shows that XCH₄ : XCO₂ ratio measurements over the southwest Amazon increase from 4.55 ppb ppm⁻¹ to about 4.65 ppb ppm⁻¹ between October–December 2013 and January–March 2014. This is a small but significant change in the ratio that suggests either enhanced CH₄ emissions and/or lower CO₂ fluxes. The two closest in situ sites to the locus of XCH₄ : XCO₂ variability (RBP and ABP) do not reproduce this change. Consequently, the in situ inversion may not accurately describe these CH₄ flux changes over the continental interior.

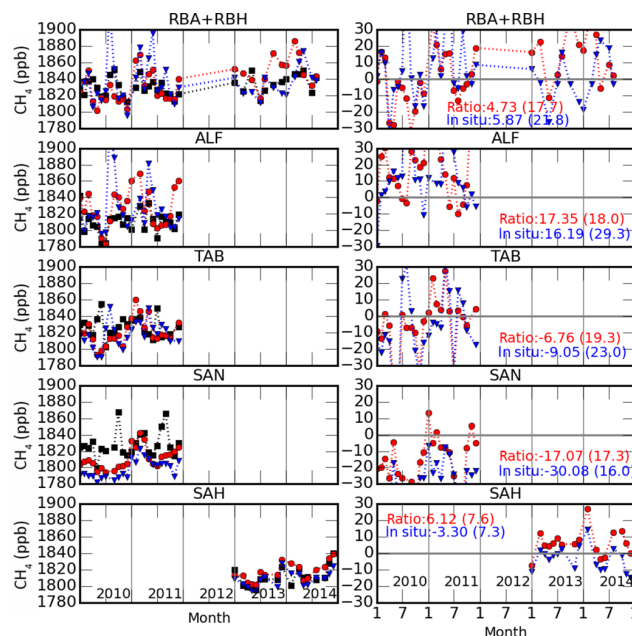
Figures 7 and 8 show that a posteriori fluxes from the ratio inversion generally decrease the mean model difference against independent AMAZONICA and ACO aircraft observations of CO₂ and CH₄ over the Amazon Basin, but with only small improvements to the associated standard deviations. At some sites, the fluxes from the ratio inversion significantly mute the rapid variations in atmospheric CO₂ and CH₄ inferred from the in situ data. Figure 7 shows that for CO₂ the greatest improvement is for the central basin sites of RBA and RBH (after 2012), where the bias reduced from −0.62 ppm to 0.01 ppm with an accompanying reduction in standard deviation from 3.7 to 2.6 ppm. We find similar but smaller reductions at another AMAZONICA site (TAB). Over other AMAZONICA and ACO sites, the im-

Table 3. The same as Table 1 but for CH₄ and CO₂ fluxes over tropical South America.

		2010	2011	2012	2013	2014
CO ₂ (GtC a ⁻¹)	Prior	0.93 (0.36)	0.56 (0.40)	0.53 (0.32)	0.37 (0.34)	0.41 (0.37)
	In situ	−0.09 (0.23)	−0.05 (0.25)	−0.01 (0.22)	0.18 (0.22)	−0.21 (0.23)
	Ratio	0.63 (0.13)	0.34 (0.14)	0.53 (0.13)	0.05 (0.13)	0.07 (0.14)
CH ₄ (Mt a ⁻¹)	Prior	44.1 (18.4)	40.3 (16.4)	40.2 (16.4)	40.2 (16.4)	40.2 (16.4)
	In situ	67.0 (11.6)	59.5 (11.3)	54.6 (11.6)	52.9 (11.9)	59.5 (11.2)
	Ratio	74.4 (3.6)	78.6 (3.8)	74.0 (3.5)	73.4 (3.2)	73.1 (3.9)

**Figure 7.** Monthly mean partial CO₂ columns at four sites over the Amazon (RBA, ALF, TAB, and SAN; Fig. 1) collected by the AMAZONICA project and two sites (RBH and SAH) after 2012 collected by the ACO project: comparison (left) and differences (right) with the GEOS-Chem model that has been sampled at the time and location of each observation and driven by fluxes inferred from the in situ (blue) and ratio (red) inversions. The mean and standard deviations (ppm) are shown in the inset of the right-hand-side panels. In the plot, we have combined the data over the AMAZONICA site RBA (for 2010 to 2012) and the ACO site of RBH (for 2012 to 2014) for a complete time series from 2010 to 2014 over the same location.

pact of GOSAT XCH₄:XCO₂ ratios are even smaller. The coarse resolution of our model that allows us to exploit efficiently the GOSAT and in situ data is one possible explanation for the large standard deviations (van der Laan-Luijkx et al., 2015; Gatti et al., 2014). Figure 8 shows that overall the ratio inversion better reproduces the AMAZONICA and ACO CH₄ data than the in situ inversion. The ratio inversion does best at SAN. It also shows a better agreement over RBA as it does for CO₂. After 2012, the ratio inversion shows a

**Figure 8.** The same as Fig. 7 but for comparison of the monthly mean partial CH₄ columns (in ppb) of the model simulations with AMAZONICA and ACO observations. Due to availability, CH₄ observations for 2012 have not been included.

positive bias at the two ACO sites (SAH and RBH). Assimilating the XCH₄:XCO₂ data reduces the standard deviations (by about 4 to 11 ppb) over ALF, TAB, and RBA (RBH after 2012), and slightly (by about 1 ppb) increase the standard deviations at SAN and SAH.

4 Summary

Building on the previously reported theory, we simultaneously inferred regional CO₂ and CH₄ fluxes from the proxy GOSAT XCH₄:XCO₂ retrievals in 2010–2014, inclusive, anchored by geographically sparse in situ mole fraction data. The main advantage of using these data directly is that the ratio is less compromised by systematic bias on spatial scales greater than typical model grid resolution (< 1000 km) and less than large-scale variations captured by ground-based

networks (< 10 000 km), which represents a limiting factor to using full-physics XCO₂ measurements. Inferring CO₂ and CH₄ fluxes together provides a self-consistent methodology.

We showed that a posteriori fluxes inferred from the GOSAT data generally outperformed the fluxes inferred only from in situ data, as expected given their greater measurement coverage. GOSAT CH₄ and CO₂ fluxes are consistent with global growth rates for CO₂ and CH₄ reported by NOAA and are generally more consistent than the results based on in situ surface data with a range of independent data collected throughout the global troposphere (e.g. aircraft profiles and ground-based total column measurements) and include new profile measurements (0–7 km) over the Amazon Basin that were collected specifically to help validate GOSAT over this geographical region.

We found that large-scale multi-year annual a posteriori CO₂ fluxes inferred from GOSAT data are similar to those inferred from the in situ surface data but with smaller uncertainties, particularly over the tropics where in situ surface data are sparse. However, we found that GOSAT data are consistent with smaller peak-to-peak seasonal amplitudes of CO₂ than either the a priori or in situ inversion, particularly over tropical and the southern extratropics, where the annual means are similar. Over the northern extratropics, GOSAT data infer a larger uptake than supported by the a priori but a smaller uptake than the corresponding in situ data. Using the individual annual means and seasonal variations during 2010–2014, we found evidence from GOSAT that the carbon balance of tropical South America was perturbed following the droughts of 2010 and 2012 when this region was a large annual source of CO₂ (0.5–0.6 PgC a^{−1}) to the atmosphere, with net annual fluxes not returning to an approximate annual balance until 2013.

We showed that GOSAT data results in significant changes with respect to a priori spatial distribution of CH₄ emission with a 40 % increase over tropical South America and tropical Asia and smaller (partially compensating) decrease over Eurasia and temperate South America. We find no evidence from GOSAT that tropical South American CH₄ fluxes were dramatically affected by the two large-scale Amazon droughts in 2010 and 2012. However, we reported that GOSAT data are consistent with double seasonal peaks in fluxes that are reproduced over the 5 years we studied: a small peak in January to April and a larger peak in June to October. Currently, we have no explanation for this phenomenon, but it is likely due to superimposed emissions from different geographical regions.

While the sensitivity of our results to model error and to the temporal and spatial resolution of fluxes requires further investigation, our analysis, in the wider context of other studies, supports the adoption of using space-borne observations of CO₂ and CH₄ to better understand the carbon cycle on the continental scale. Well-known weaknesses of these data (e.g. biases in spatial and temporal coverage) can be partially overcome by integrating them with information from other networks and by judicious use of atmospheric chemistry transport models. The next obvious step is to understand how we can improve source attribution of CO₂ and CH₄ without necessarily resorting to the assumption, as used here and elsewhere, that a priori fossil fuel emission estimates are correct. Source attribution can be sometimes achieved by exploiting knowledge of spatial distributions of different sources, but techniques that allow more rigorous exploitation of multi-gas correlations must be developed and incorporated into data assimilation systems that will eventually form the backbone to operational systems (e.g. EU Copernicus Atmospheric Monitoring Service to atmospheric CO₂).

Data availability. The University of Leicester GOSAT Proxy XCH₄ v6.0 data are available from <http://www.leos.le.ac.uk/data/GHG/GOSAT/v6.0/>. The password can be provided by R. Parker on request. A description of this data set can be found in Buchwitz et al. (2017). These data are also part of the ESA GHG-CCI Climate Research Data Package v3 (<http://www.esa-ghg-cci.org/>, Buchwitz et al., 2017). AMAZONICA data are available from <http://www.ccst.inpe.br/projetos/lagee/> (Gatti et al., 2014). TCCON data were obtained from the TCCON data archive, hosted by the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory, Oak Ridge, Tennessee (US), doi:10.14291/tcon.archive/1348407 (Blumenstock et al., 2014). CARIBIC CO₂ and CH₄ data are available on request from A. Zahn.

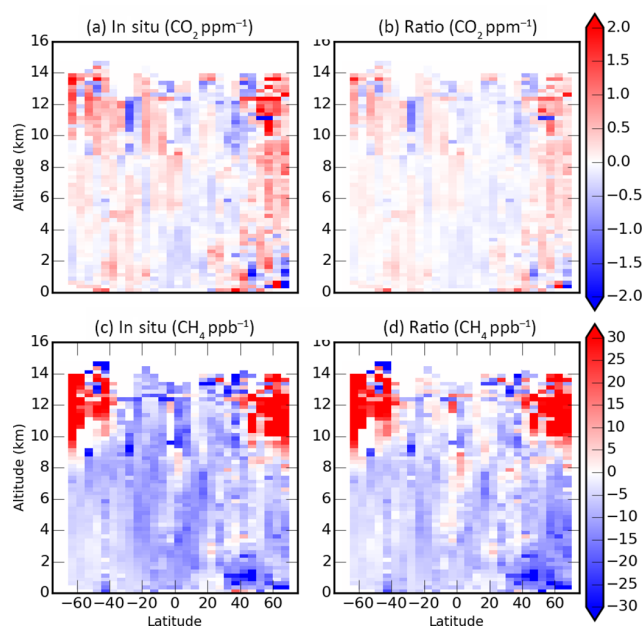


Figure A1. Differences between observed and (a, c) in situ and (b, d) ratio a posteriori model (a, b) CO₂ and (c, d) CH₄ mole fractions observed during HIPPO experiments 1–5 (Wofsy et al., 2011) that cover individual periods during 2009, 2010, and 2011. Model and observation are gridded on a latitude interval of 5° and a vertical interval of 500 m.

Appendix A: Wider geographical model evaluation

We use independent observations to evaluate the a posteriori model concentrations that correspond to the flux estimates, acknowledging limitations associated with sparse observation coverage and atmospheric transport model errors (Chevallier et al., 2014). We sample the GEOS-Chem atmospheric chemistry transport at the time and location of each individual observation.

A1 HIPPO

Figures A1 and A2 show that the ratio inversion is marginally more consistent with HIPPO XCO₂ data than the in situ inversion, but the spatial error structure is qualitatively similar. The ratio inversion has a positive bias of 0.2 ppm and standard deviation of 1.3 ppm compared to the in situ inversion that has a positive bias of 0.3 ppm and standard deviation of 1.3 ppm. The largest standard deviations (up to 0.8 %) reflect the ability of models to reproduce small-scale variations, particularly at the lowest (the planet boundary layer) and the highest (the upper troposphere and lower stratosphere) altitudes. We find small differences (generally within 1 ppm) below 4–6 km between 40° S and 40° N, and much larger differences (up to 2 ppm) in the upper troposphere and in the lower stratosphere north of 45° N.

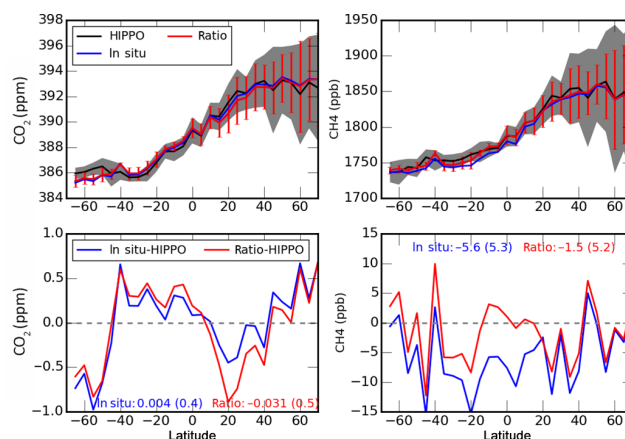


Figure A2. (Top) HIPPO-3 (Wofsy et al., 2011), May 2010, and a posteriori model partial columns of (left) CO₂ and (right) CH₄ as a function of latitude over the Pacific Ocean, and (bottom) the differences between the observations and the in situ and ratio inversions. The mean biases (standard deviations) between the model and data are shown in the inset of the lower panels. Data and model values are binned into 5° mass-weighted latitude boxes.

The ratio and in situ inversions show similar spatial structure to HIPPO XCH₄ data. We find a small negative bias (0–15 ppb) in the middle and lower troposphere between 40° S and 40° N and a larger positive bias (by over 20 ppb) in the extratropical upper troposphere/lower stratosphere. We find the largest discrepancies between model and observed XCH₄ in the higher-latitude lower stratosphere, in agreement with previous studies (e.g. Alexe et al., 2015 and Pandey et al., 2016), which is mainly due to difficulties in modelling stratospheric chemical processes. As a result, the ratio inversion and the in situ inversions have similar biases of 0.6 and 0.1 ppb, respectively, as well as similar standard deviations of 27.7 versus 27.5 ppb, respectively.

Figure A2 shows that the two a posteriori models reproduce the hemispheric CO₂ gradient, typical for boreal spring months, observed by the HIPPO-3 experiment. Compared to the in situ inversion, the ratio inversion has a larger negative bias (−0.8 versus −0.4 ppm) around 20° N, in contrast to a slightly larger positive bias over most of the Southern Hemisphere. We find that the overall model bias and associated standard deviation of the gridded partial CO₂ columns are very small (biases < 0.01 ppm and standard deviation < 0.6 ppm). Figure A2 shows that the two a posteriori models also reproduce the hemispheric CH₄ gradient observed by the HIPPO-3 experiment. Compared to the in situ inversion, the proxy GOSAT XCH₄ : XCO₂ data significantly reduce the negative bias of the CH₄ concentrations (by up to 10 ppb) over the tropical regions. The overall bias for the gridded CH₄ partial columns is reduced from −5.6 ppb for the in situ inversion to −1.5 ppb for the ratio inversion.

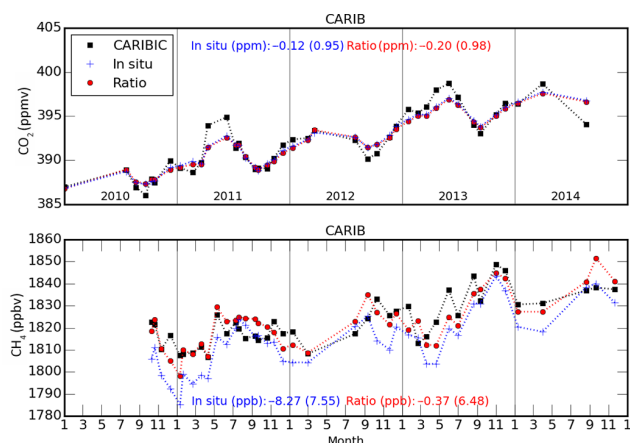


Figure A3. Monthly means CARIBIC and a posteriori model (left) CO₂ and (right) CH₄ mole fractions collected in the tropical middle/upper troposphere (<300 hPa) between 30° S and 30° N. The monthly mean biases (standard deviations) of the model minus data differences are shown in the inset.

A2 CARIBIC

Figure A3 shows that the two a posteriori models reproduce the observed annual trend of CO₂ monthly means and the observed seasonal cycle with smaller amplitude. Underestimation of the seasonal cycle of the upper-tropospheric CO₂ concentrations is well documented, and believed to be caused by a deficiency in modelling vertical transport (Stephens et al., 2007). Figure A3 also shows that the a posteriori models reproduce the observed trend and seasonal variation of atmospheric CH₄ in the tropical middle/upper troposphere. The ratio inversion has a smaller bias (−0.37 ppb) than the in situ inversion (−8.27 ppb) but has only modestly improved the associated standard deviation by 15 % from 7.55 to 6.48 ppb.

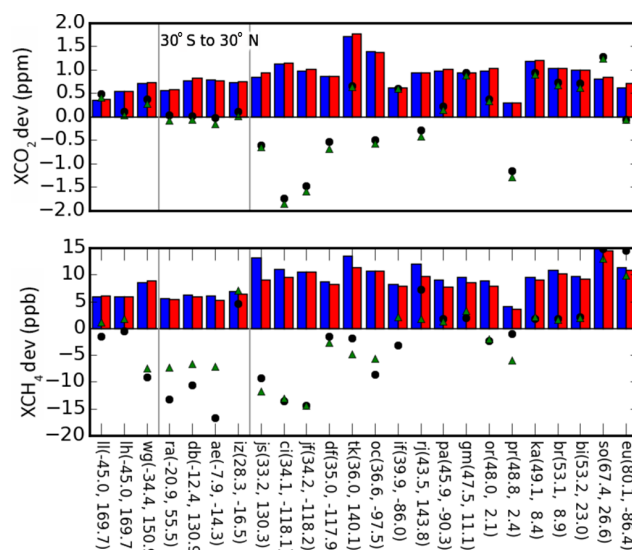


Figure A4. Mean multi-year statistics (2010–2014) of the differences between TCCON (top) XCO₂ and (bottom) XCH₄ measurements and the a posteriori models. Blue and red bars denote the standard deviations between TCCON and the in situ and ratio a posteriori model, respectively. Black circles and green triangles denote the mean deviation of the TCCON and the in situ and ratio a posteriori models.

A3 TCCON

Figure A4 shows that the two a posteriori models have a similar level of agreement with 24 independent TCCON XCO₂ retrievals. For most of these sites, the model XCO₂ bias is well within 1.0 ppm, and the standard deviation is between 0.6 and 1.5 ppm. The two exceptions are sites around Los Angeles, CA, USA: cj (34.1° N, 118.1° W) and jf (34.2° N, 118.2° W), where the models underestimate atmospheric XCO₂ by 1.5–2.0 ppm, which we attribute to our coarse model resolution. Figure A4 also shows that assimilating GOSAT XCH₄ : XCO₂ proxy data significantly reduces the model XCH₄ bias by up to 10 ppb over low-latitude TCCON sites. The GOSAT data also help to reduce the standard deviations over most of the 24 sites.

Author contributions. L. Feng and P. I. Palmer designed the experiments and wrote the paper; H. Bösch, R. J. Parker, and Alex Webb provided the GOSAT XCO₂ and XCH₄ data; N. M. Deutscher, D. G. Feist, R. Kivi, I. Morino, O. Uchino, F. Hase, R. Sussmann, and K. Strong provided access to TCCON XCO₂ and XCH₄ data; A. Zahn provided access to CARIBIC CO₂ and CH₄ mole fraction data. L. V. Gatti, E. Gloor, C. S. C. Correia, L. G. Domingues, and J. B. Miller provided access to aircraft data (AMAZONICA and ACO) over the Amazon Basin. J. Wang and Y. Liu provided a preliminary evaluation of CO₂ and CH₄ fluxes over China. All co-authors provided comments and suggestions on the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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